A&A manuscript no.
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ASTRONOMY
AND
ASTROPHYSICS
1.2.2008

The stellar origin of ^{7}Li

Do AGB stars contribute a substantial fraction of the local Galactic lithium abundance?

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Received 22 December 2000/ Accepted 28 May 2001

Abstract. We adopt up-to-date ^{7}Li yields from asymptotic giant branch stars in order to study the temporal evolution of ^{7}Li in the solar neighbourhood in the context of a revised version of the two-infall model for the chemical evolution of our galaxy.

We consider several lithium stellar sources besides the asymptotic giant branch stars such as Type II supernovae, novae, low-mass giants as well as Galactic cosmic rays and low-mass X-ray binaries.

We conclude that asymptotic giant branch stars cannot be considered as important ^{7}Li producers as believed in so far and that the contribution of low-mass giants and novae is necessary to reproduce the steep rise of the ^{7}Li abundance in disk stars as well as the meteoritic ^{7}Li abundance. Lithium production in low-mass X-ray binaries hardly affects the temporal evolution of ^{7}Li in the solar neighbourhood.

Key words: Galaxy: abundances – Galaxy: evolution – Galaxy: solar neighbourhood

1. Introduction

The upper envelope of the observed $\log \epsilon(^7\mathrm{Li})$ vs. [Fe/H][1] diagram is generally believed to reflect the ^{7}Li enrichment history of the interstellar medium (ISM) in the solar neighbourhood. Therefore, it can be used to constrain models of Galactic chemical evolution aiming at explaining the temporal evolution of this element. The major features of the observational diagram are *i)* a large plateau at low metallicities (*lithium-metallicity plateau*, firstly pointed out by Rebolo, Molaro, & Beckman 1988) followed by *ii)* a steep rise afterwards.

A large spread is observed in the data for Population I dwarfs, increasing with metallicity and commonly interpreted as a signature of processes of lithium dilution and/or destruction in stars.

Field halo dwarfs hotter than 5700 K exhibit a weaker dependence on effective temperature, T_{eff}, and metallicity, [Fe/H], and a smaller dispersion than seen in Population I stars. However, ultra-Li-deficient, warm, halo stars do exist (Spite, Maillard, & Spite 1984; Hobbs & Mathieu 1991; Hobbs, Welty, & Thorburn 1991; Thorburn 1992; Thorburn & Beers 1993; Spite et al. 1993; Ryan et al. 2001a), complicating the overall picture. Actually, there is vigorous debate about the existence and magnitude of any dispersion, and there are active controversies about trends with T_{eff} and [Fe/H] (Thorburn 1994; Molaro, Primas, & Bonifacio 1995; Ryan et al. 1996; Spite et al. 1996; Bonifacio & Molaro 1997). In particular, the existence of trends of ^{7}Li with metallicity would be a signature of Galactic chemical evolution.

By comparing theoretical stellar evolution models with the observational Population II lithium data one can obtain bounds on stellar lithium depletion in halo stars. This has implications for stellar structure, Galactic chemical evolution, and Big Bang nucleosynthesis (BBN). From a combination of the dispersion in the data, the detection of the fragile isotope ^{6}Li in some halo stars (Smith, Lambert, & Nissen 1993, 1998; Hobbs & Thorburn 1994, 1997; Cayrel et al. 1999; Nissen et al. 1999, 2000), and the flatness of the halo plateau a depletion at the 0.15 − 0.2 dex level, with a firm upper bound of 0.5 − 0.6 dex, has been suggested (Pinsonneault, Charbonnel, & Deliyannis 2000; Pinsonneault et al. 1999). In this scenario, the primordial

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[1] Here we use the notation $[\mathrm{X/H}] = \log(\mathrm{X/H})_{\mathrm{star}} - \log(\mathrm{X/H})_\odot$ and $\log\epsilon(\mathrm{X}) = \log(\mathrm{N_X/N_H}) + 12$, where X and H are the abundances by mass and $\mathrm{N_X}$ and $\mathrm{N_H}$ are the number of atoms of the element X and hydrogen, respectively.

lithium abundance should be (slightly) higher than what we effectively see.

However, one could ask whether there is any depletion at all: are we directly seeing the primordial lithium abundance (*e.g.*, Bonifacio & Molaro 1997), or is the primordial lithium abundance lower than the observed plateau value because of a significant early contribution from Galactic chemical evolution (Ryan, Norris, & Beers 1999; Ryan et al. 2000; Suzuki, Yoshii, & Beers 2000)? It seems that consistency of the BBN predictions and light element abundances hinges on some depletion of ^{7}Li in old halo stars (Burles, Nollett, & Turner 2000), although in our view a clear answer is still precluded. For this reason we will investigate the effect of adopting three different values for the primordial lithium abundance in the chemical evolution code.

In the standard framework of the origin and evolution of the light elements, ^{7}Li is produced in significant abundance ($\sim 1/10$ solar) in BBN. The processes of spallation of Galactic cosmic rays (GCRs) composed of p, α and C, N, and O on interstellar C, N, and O and p, α nuclei, respectively, joint to an α-α fusion channel are responsible for $\sim 20-30\,\%$ of the local Galactic abundance of ^{7}Li (*e.g.*, Reeves, Fowler, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971). The remaining unexplained fraction of the solar abundance has to originate from a stellar source.

Different studies trying to explain the observed $\log\epsilon(^7\mathrm{Li})$ vs. [Fe/H] trend by taking into account different astrophysical sites for ^{7}Li production have appeared in the literature (*e.g.*, D'Antona & Matteucci 1991; Matteucci, D'Antona, & Timmes 1995; Abia, Isern, & Canal 1995; Romano et al. 1999, hereafter Paper I; Casuso & Beckman 2000; Ryan et al. 2001b). However, most of them focused on two or three categories of ^{7}Li producers alone, while neglecting the others. The main purpose of this work is to study the interplay between several categories of ^{7}Li producers in order to explain both the rise from the lithium-metallicity plateau and the meteoritic abundance of ^{7}Li; in particular, to test the effect of new detailed nucleosynthesis calculations by Ventura, D'Antona & Mazzitelli(2000) on the ^{7}Li produced in asymptotic giant branch (AGB) stars. To do that, we adopt a chemical evolution model which already reproduces the majority of the observational constraints in the Milky Way (Chiappini, Matteucci, & Gratton 1997; Chiappini, Matteucci, & Romano 2001).

In Section 2 we describe the chemical evolution model and the various lithium producers. In Section 3 the results are presented and in Section 4 some conclusions are drawn.

2. The model

2.1. Basic assumptions

The adopted model is a revised version of the two-infall model of Chiappini et al. (1997), especially devised in order to study the radial properties of the Galactic disk (Chiappini et al. 2001).

The Galaxy is assumed to form out of two main episodes of accretion: during the first one the halo/thick-disk forms; during the second one the thin-disk is built up, mainly out of matter of primordial chemical composition, except for some fraction of enriched gas from the halo. The stellar generations forming during the Galactic lifetime distribute their stellar masses according to a Scalo initial mass function (IMF). The IMF is kept constant in space and time. The star formation, proportional to both the gas surface density and the total mass surface density at every time, is a self-regulated process, in the sense that it stops when the gas surface density falls below a certain critical threshold and it starts again when an above-threshold value is recovered due to infall of primordial matter coupled to restoration of gaseous matter by dying stars.

As far as the solar vicinity is concerned, the major differences with the Chiappini et al. (1997) model which we adopted in Paper I are the following: the sun is located at a distance of 8 kpc from the Galactic center, rather than 10 kpc; the adopted Galactic age is 14 Gyr, rather than 15 Gyr; the timescales for mass accretion in the halo/thick-disk and thin-disk components are 0.8 and 7 Gyr, respectively (rather than 2 and 8 Gyr). We refer the reader to Chiappini et al. (1997, 2001) for a full description of model parameters and results. Here we will only address the aspects more strictly related to ^{7}Li evolution (production in different astrophysical environments and astration in stars).

2.2. Lithium synthesis prescriptions

The primordial ^{7}Li abundance is set to be $\log\epsilon(^7\mathrm{Li})_P$ = 2.2 dex (Bonifacio & Molaro 1997). The cases $\log\epsilon(^7\mathrm{Li})_P$ = 2.09 dex (Ryan et al. 2000) and 2.4 dex (*e.g.*, Pinsonneault et al. 2000) are also investigated (see discussion in Section 1).

Lithium astration in stars of all masses is taken into account in a simple way, by assuming that each stellar generation fully destroyes the lithium present in the progenitor gas out of which it forms.

As far as the ^{7}Li synthesis is concerned, we include in the chemical evolution code the following ^{7}Li sources: the ν-process in Type II supernovae (SNe), AGB stars which undergo the hot bottom burning (HBB) process, low-mass red giants, novae, and GCRs. Moreover, we try to argue whether low-mass X-ray binaries (LMXBs) could play a role regarding the production of ^{7}Li at a Galactic scale. The hypothesis of instantaneous recycling is relaxed and the stellar lifetimes are taken into account in great detail: according to this, different lithium sources restore their newly synthesized ^{7}Li on different timescales. This is an important point to stress, since the shape of the growth

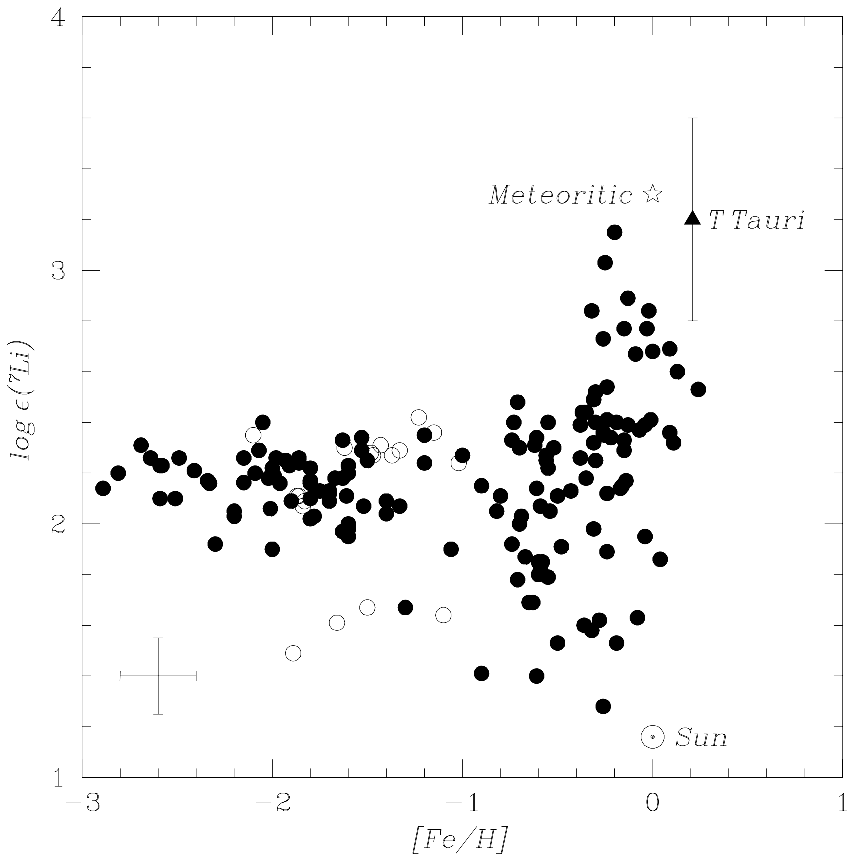

Fig. 1. The observational $\log \epsilon(^7\mathrm{Li})$ vs. [Fe/H] diagram. *Filled circles*: data from the compilation of Romano et al. (1999); *open circles*: new measurements by Ryan et al. (2001b); both symbols are referring to objects with $T_{\mathrm{eff}} \geq$ 5700 K. The solar abundance is taken from Anders & Grevesse (1989), the meteoritic one is from Nichiporuk & Moore (1974). The ^{7}Li abundance in T Tauri stars we show is the one suggested by Stout-Batalha, Batalha, & Basri (2000), at 2-σ error.

in the $\log \epsilon(^7\mathrm{Li})$ vs. [Fe/H] diagram can be justified just in terms of timescales of ^{7}Li production.

2.2.1. Type II supernovae

The neutrino flux emitted from a cooling proto-neutron star alters the traditional outcome of explosive nucleosynthesis from Type II SNe. ^{7}Li production takes place mostly in the helium shell. The key reaction for producing ^{7}Li is the excitation of ^{4}He by μ- and τ-neutrinos (and their anti-neutrinos) through inelastic scattering, followed by nuclear de-excitation via emission of a neutron or a proton. The decay products then react with the abundant ^{4}He to produce ^{7}Li and ^{7}Be (which decays later to ^{7}Li) (see Hartmann et al. 1999 and references therein).

Unfortunately, no observational evidence exists supporting that Type II SNe are able to enrich the ISM in ^{7}Li. Therefore, the estimated theoretical yields are very uncertain. In particular, they are mostly sensitive to the properties of the neutrino flux. ν-process yields for a model grid in stellar mass and metallicity have been computed by Woosley & Weaver (1995). We included ^{7}Li + ^{7}Be yields from Woosley & Weaver in a model for the chemical evolution of the solar neighbourhood and showed that, in order to reproduce the extension of the lithium-metallicity plateau, we had to require a reduction of these yields by at least a factor of 2 (Paper I). Our claim was in agreement with the upper limit on the contribution to ^{7}Li production by ν-induced nucleosynthesis suggested by Ramaty et al. (1997). Moreover, observations of Be and B in stars covering 3 orders of magnitude in metallicity ($-3.0 \leq$ [Fe/H] $\leq +0.0$) suggest a scenario for light element production which argues against the majority of B being produced in the ν-process (Duncan et al. 1997), thus putting another, independent constraint on the ν-process yields.

In the light of the above considerations, we will take here as ^{7}Li + ^{7}Be yields from Type II SNe those by Woosley & Weaver (1995) reduced to a half, although an even larger reduction factor could be required (Vangioni-Flam et al. 1996).

2.2.2. AGB stars

AGB stars have been recognized to be ^{7}Li producers since long ago (Smith & Lambert 1989, 1990; Sackmann & Boothroyd 1992). According to Sackmann & Boothroyd, ^{7}Li production would occur in the mass range $M \sim 4-6\ M_{\odot}$, when the temperature at the base of the convective envelope exceeds 50×10^6 K and the ^{7}Be transport mechanism (Cameron & Fowler 1971) works. Under these conditions, ^{7}Li abundances as large as $\log \epsilon(^7\mathrm{Li}) \sim 4-4.5$ can be achieved in the external layers, in principle allow-

Table 1. ^{7}Li yields from AGB stars. The yield is the fraction of the initial mass of the star which is ejected as newly produced ^{7}Li during the whole stellar lifetime.

$M_{init}(M_\odot)$	^{7}Li yield ($\eta_R = 0.01$)	^{7}Li yield ($\eta_R = 0.10$)
$Z = 0.02$		
3.5	1.28E-11	5.07E-11
4.0	3.34E-10	1.78E-09
4.5	6.25E-10	6.53E-09
5.0	1.41E-09	1.09E-08
5.5	3.11E-09	1.87E-08
6.0	5.21E-09	2.47E-08
$Z = 0.01$		
3.3	4.03E-10	–
3.5	4.03E-10	1.43E-11
4.0	6.08E-10	4.94E-09
4.5	7.29E-10	6.49E-09
5.0	1.29E-09	9.61E-09
5.5	1.89E-09	1.69E-08
6.0	4.10E-09	2.31E-08
$Z = 0.004$		
2.2	1.71E-11	
2.5	1.70E-11	
3.0	5.00E-10	
3.5	3.65E-10	
4.0	3.60E-10	
4.5	3.45E-10	
5.0	4.17E-10	
5.5	5.09E-10	
$Z = 0.001$		
3.0	4.12E-10	1.34E-11
3.5	2.58E-10	2.21E-10
4.0	1.97E-10	2.22E-09
4.5	1.20E-10	2.14E-09
5.0	2.73E-10	2.29E-09
5.5	2.47E-10	2.07E-09
$Z = 0.0006$		
2.5	1.05E-11	
3.0	3.91E-10	
3.5	2.26E-10	
4.0	1.92E-10	
4.5	1.40E-10	
5.0	1.20E-10	
5.5	1.80E-10	
$Z = 0.0002$		
2.5	2.01E-10	
3.0	4.20E-10	
3.5	2.69E-10	
4.0	1.75E-10	
4.5	1.36E-10	
5.0	1.14E-10	

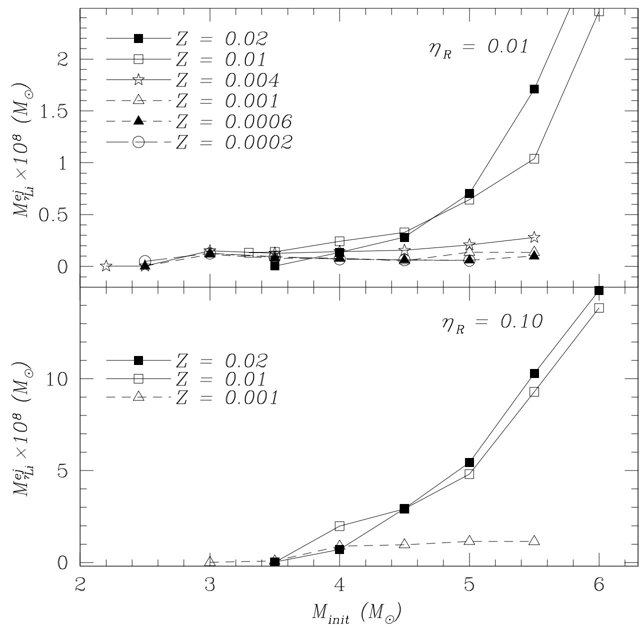

Fig. 2. Mass ejected in the form of newly produced ^{7}Li during the whole stellar lifetime as a function of the initial mass of the star, at various metallicities and for two choices of the Reimer's parameter of mass loss, η_R. ^{7}Li production occur along the AGB, during the termally pulsing phase.

ing these stars to efficiently pollute the ISM via mass loss and/or planetary nebula (PN) ejection. A metallicity effect would also prevent these stars from contributing significant amounts of newly synthesized ^{7}Li at early times (Plez, Smith, & Lambert 1993; see also discussions in Matteucci et al. 1995 and Paper I), thus helping to keep the lithium-metallicity plateau flat until an ISM metallicity of [Fe/H] ~ -0.5 dex is achieved, in agreement with observations (Fig. 1). On these grounds, massive AGBs were proposed as a significant source of lithium Galactic enrichment (*e.g.*, D'Antona & Matteucci 1991; Matteucci et al. 1995), even if a reliable computation of the ^{7}Li yields was still in demand at that time.

Very recently such a computational task has been accomplished by means of the code ATON 2.0 (Ventura et al. 1998). This computational tool is especially devised to follow the AGB HBB phase: it includes diffusive mixing coupled to nuclear evolution and it treats turbulence in the Full Spectrum of Turbulence model (Canuto & Mazzitelli 1991; Canuto, Goldman & Mazzitelli 1996). Results for $Z = 0.01$ can be found in Ventura et al. (2000). Here we enlarge the model grid to a wide range of metallicities ($Z = 0.0002$, 0.0006, 0.001, 0.004, and 0.02) and include it in a code for the chemical evolution of the solar neighbourhood. The complete, enlarged model grid is shown in Table 1 and Fig. 2 for two choices of the Reimer's factor η_R entering Blöcker's (1995) prescription for mass loss.

Observational evidence suggests that the lower value of η_R should be preferred, at least at low metallicities (Ventura et al. 2000).

Lithium production during the AGB phase is very efficient, but in the last phases of evolution the fast ^{3}He consumption implies a soon decrease in the ^{7}Li abundance. As a result, the net yields are too low to significantly contribute to ^{7}Li enrichment on a Galactic scale (see Section 3 for detailed chemical evolution results).

2.2.3. Low-mass red giants

Population I red giants usually have lithium abundances lying in the range $-1 < \log\epsilon(^7\mathrm{Li}) < 1$ (Lambert, Dominy, & Sivertsen 1980; Brown et al. 1989). However, a few ($\sim 1\,\%$) of them show lithium abundances far in excess of standard predictions (*e.g.*, Wallerstein & Sneden 1982; Hanni 1984; Brown et al. 1989; da Silva, de la Reza, & Barbuy 1995), occasionally having abundances much higher than the present ISM value (*e.g.*, de la Reza, Drake, & da Silva 1996; Balachandran et al. 2000). Frequently, these Li-rich red giants have large infrared excesses, which are interpreted as associated circumstellar dust shells. Interestingly enough, these Li-rich giants have not yet reached the AGB, and at least some of them are observed to be low-mass stars; thus they cannot have experienced ^{7}Li creation via HBB, and do not enter in the group we have analyzed in detail in the previous paragraphs.

A scenario has been proposed in which all low-mass giants ($M < 2.5\ M_\odot$) suffer a prompt ^{7}Li enrichment in the upper part of the red giant branch (RGB), after the first dredge-up and before the RGB tip. A circumstellar dusty shell enriched with ^{7}Li forms, which detaches later from the star when the internal mechanism of ^{7}Li production ceases. In this way, the ISM is polluted by newly synthesized ^{7}Li (de la Reza et al. 1996, 1997). Using this stellar internal prompt ^{7}Li enrichment scenario coupled to mass loss, de la Reza et al. (2000) have explored the possibility of ^{7}Li enrichment by low-mass, metal-poor RGB stars in globular clusters and suggested them as a potential source of ^{7}Li enrichment in the Galactic disk.

Maybe the best mechanism for producing the ^{7}Li photospheric enrichment for these low-mass giants is the cool bottom process (CBP) based on ^{7}Be production from ^{3}He in the H-burning shell, followed by transport of the fresh ^{7}Be up to the base of the convective layer to be then taken to the cooler stellar surface where it decays to ^{7}Li (Sackmann & Boothroyd 1999). In this scenario, a discontinuous ^{7}Li enrichment is linked to mass loss, and the process can be repeated depending on the availability of ^{3}He. Contrary to AGB stars, where ^{7}Be is quickly mixed away by ordinary convection, in RGB stars some extra-mixing is required. Denissenkov & Weiss (2000) have proposed a mechanism which is able to trigger the extra-mixing: a giant planet (or brown dwarf) is engulfed by a red giant; this external event activates inside the giant the ^{7}Be transport mechanism which results in producing ^{7}Li. The great advantage of this solution is that it can account not only for the Li-production but also for the subsequent Li-depletion, on a quick timescale consistent with the results of de la Reza et al. (1996). The amount of ^{7}Li produced in a single episode of lithium enrichment can exceed $\log\epsilon(^7\mathrm{Li}) \sim 4$, but it is critically related to the details of the extra-mixing mechanism (Sackmann & Boothroyd 1999).

The amount of ^{7}Li injected into the ISM depends strongly on the parameters of the lithium enrichment scenario: the size and timescales of the lithium enhancements, the magnitude and timescales of the mass loss, and whether, how often, and at what points on the RGB such enhancement episodes occur. de la Reza et al. (1996, 1997), with $\log\epsilon(^7\mathrm{Li}) \leq 4$ for timescales $\leq 10^5$ yr, mass loss in the range $10^{-7} - 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, and recurrence of ~ 10 times per star at $\log L \sim 2$, predict an average ^{7}Li abundance in the total amount of material ejected from low-mass stars less than $\sim 1\,\%$ of the cosmic abundance, a negligible quantity. However, if at least some ^{7}Li enrichment episodes occur near the tip of the RGB, this average ^{7}Li abundance could be more than an order of magnitude larger, yielding to a non-negligible ^{7}Li enrichment of the ISM (Sackmann & Boothroyd 1999; but see also Charbonnel & Balachandran 2000).

Here we investigate this latter scenario, more favourable to ^{7}Li production. We assume that: *i)* all stars in the mass range $M = 1-2\ M_\odot$ experience enhanced RGB lithium abundances in conjunction with episodic mass loss, for a period lasting $\sim 10^7$ yr on the whole (whatever the timescale of a single lithium enhancement episode and the recurrence of the phenomenon may be); *ii)* the photospheric ^{7}Li enrichment occurs near the tip of the RGB, so that the mass loss is at work at the highest rates ($\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$); *iii)* the surface lithium abundance is set to $\log\epsilon(^7\mathrm{Li}) = 4$ for each star. (Obviously, a reliable computation of the ^{7}Li yields from stars in this mass range would be highly desirable.)

2.2.4. Classical novae

In the past decades, contradictory views on lithium production from novae have appeared in the literature. D'Antona & Matteucci (1991), by using the results of Starrfield et al. (1978) on ^{7}Li synthesis in nova outbursts, concluded that novae would represent a significant source for the present ISM ^{7}Li content. Later, Boffin et al. (1993) ruled out novae as lithium producers at a Galactic level, but a subsequent check by Hernanz et al. (1996) plotted out again large overproduction factors relative to the solar abundance for ^{7}Be (and hence ^{7}Li)! More recently, José & Hernanz (1998) computed a grid of hydrodynamical nova models, providing ^{7}Li yields which we used in Paper I. In that study, we emphasized the important role played by novae in reproducing the late, steep rise from the lithium-metallicity plateau: since the nova eruptions come from

systems containing a cool white dwarf (WD), we have to wait a long time, given by the lifetime of the progenitor star plus a suitable cooling time, before observing any production from these stellar ^{7}Li factories.

In order to include the nova system nucleosynthesis in the chemical evolution code, we had to make a number of assumptions: *i)* the nova system formation rate at any time t is a constant fraction of the WD formation rate at a previous time $t - \Delta t$ (D'Antona & Matteucci 1991); this constant fraction is fixed by the rate of nova outbursts observed in the Galaxy at the present time ($20 - 30$ yr^{-1}, Shafter 1997); *ii)* the value of Δt is set in order to guarantee the cooling of the WD at a level that ensures a strong enough nova burst; *iii)* 10^4 nova outbursts are assumed to occur on average in each nova system (Bath & Shaviv 1978; Shara et al. 1986); *iv)* 30 % of novae occur in systems containing ONeMg WDs, while the remaining 70 % occur in systems containing CO WDs (*e.g.*, Gehrz et al. 1998).

In this study we will adopt the same nucleosynthesis prescriptions on lithium production from nova outbursts we used in Paper I. Besides, we will investigate in more detail how tightly our results are bound to the assumptions we made.

2.2.5. GCR nucleosynthesis

^{7}Li is also produced in spallation and fusion processes associated with cosmic rays (*e.g.*, Reeves et al. 1970; Meneguzzi et al. 1971).

A GCR production of ^{7}Li at early times could complicate the derivation of the primordial ^{7}Li abundance from Population II star data also under the simplifying hypothesis that ^{7}Li depletion in halo stars is negligible. In principle, by using information on Be and ^{6}Li one can set an upper bound to the fraction of ^{7}Li produced by GCRs in the halo phase, in the context of a given model of GCR nucleosynthesis (see Olive & Fields 1999 and refs. therein). However, theoretical predictions are very uncertain, since they depend on the details of the cosmic ray sources and propagation, which are still poorly known. At epochs when [Fe/H] exceeds about -1 dex, nucleosynthesis in a variety of other Galactic objects (see previous paragraphs) produce the bulk of ^{7}Li. In particular, GCRs are expected to contribute no more than 25 % of the meteoritic ^{7}Li abundance (see arguments in Reeves 1993).

In this work we will use the absolute yields from GCRs by Lemoine, Vangioni-Flam, & Cassé (1998) which we already used in Paper I.

2.2.6. Low-mass X-ray binaries

The high Li abundances ($20 - 200$ times the solar value) observed in the low-mass secondaries of several soft X-ray transients (SXTs) (Martín et al. 1992, 1994a; Marsh, Robinson, & Wood 1994; Filippenko, Matheson, & Barth 1995; Harlaftis, Horne, & Filippenko 1996; Martín et al. 1996) imply a source of recent Li production in these systems (Martín et al. 1994a; Martín, Spruit, & van Paradijs 1994b).

SXTs, also referred to as X-ray novae, are a subclass of LMXBs which are characterized by strong outbursts lasting several weeks, followed by long quiescent periods ranging from several months to tens of years. There are three main scenarios for the formation of these X-ray transients: *i)* initially, the system is a wide binary composed of a very massive primary and a solar-type secondary. When the primary evolves off the main sequence, the secondary is engulfed in the giant's atmosphere. The system enters a common envelope phase which ends with core collapse and SN explosion, or nonexplosive formation of a black hole. *ii)* Accretion-induced collapse of a massive WD. *iii)* The low-mass secondary is captured by the compact object.

Martín et al. (1994a) have argued that energetic processes associated with the accretion onto the compact object produce the fast particles responsible for Li production. Li would be produced in the accretion disk by spallation of CNO nuclei or by α-α reactions and might leave the system through a disk-fed wind; some of the disk wind would then be captured by the secondary, enriching it with Li (Martín et al. 1994b and refs. therein). The abundances observed in the late-type secondaries one month or longer after a burst must represent closely the average production over many outbursts (Martín et al. 1994b). Therefore, from the amount of Li observed at the surface of the secondary one can in principle infer the number of Li atoms created during the outburst that escape and enrich the ISM (*e.g.*, Martín et al. 1994b; Yi & Narayan 1997).

To estimate the role these transient systems play as producers of lithium at a Galactic scale we assume that: *i)* at any time t, the LMXB formation rate is a constant fraction of the Type II SN rate (with Type II SN progenitors in the mass range $8 - 100\ M_\odot$). This constant fraction is fixed by the request that the total number of LMXBs that are in quiescence at present is ~ 1000, as estimated by Tanaka & Shibazaki (1996) for an average recurrence period of 50 yr. However, note that this number could be as low as ~ 200. *ii)* The rate at which Li is ejected into the ISM by a single LMXB is of the order of $\sim 10^{\mathbf{-13}}\ M_\odot$ yr$^{\mathbf{-1}}$, which is the rate of Li production from outbursts for black hole SXTs obtained by using quite optimistic estimates of the various parameters involved in the computation (Yi & Narayan 1997). However, it should be noted that each neutron star SXT would actually eject Li at a rate about an order of magnitude lower. What's more, we are completely neglecting the fact that during quiescence the rate of Li ejection comes down to lower values. *iii)* Each LMXB produces Li for ~ 10 billion years; then, the secondary ends up as a WD and the compact object cannot accrete material any longer. Note that if the mass of the secondary is in the range $2 - 3\ M_\odot$, Li production

should last for shorter periods, ranging from ~ 1.5 Gyr to a few Myrs.

3. Results

3.1. Are AGB stars contributing ^{7}Li at a Galactic level?

The HBB process has been demonstrated to be able to explain the high ^{7}Li abundances observed in the most Li-rich stars which undergo the AGB phase, if coupled to a mixing mechanism (ordinary convective diffusion is shown to work) which takes the newly synthesized ^{7}Be to a cooler, external region where it can decay and survive as ^{7}Li (*e.g.*, Sackmann & Boothroyd 1992). It has also been stated that these Li-rich stars might enrich the ISM with significant amounts of ^{7}Li and represent, perhaps, the major source of ^{7}Li in a galaxy (Smith & Lambert 1990; D'Antona & Matteucci 1991; Sackmann & Boothroyd 1992; Matteucci et al. 1995). However, detailed computations giving as a result the net ^{7}Li yields for a model grid in stellar mass and metallicity (see Section 2.2.2) argue against previous findings and suggest that AGB stars cannot enrich the interstellar matter with significant amounts of lithium, in spite to the fact that large ^{7}Li abundances are indeed reached in the external layers at some stages of the evolution (Ventura et al. 2000). To prove this, one needs to include the model grid of ^{7}Li yields in a code for the chemical evolution of the solar vicinity, and this is what we have done.

In Fig. 3 we show the effect of employing the new vs. the old prescriptions on ^{7}Li production from AGB stars in models where these stars are the only ^{7}Li producers. The curves labelled *MDT95* and *Paper I* refer to theoretical trends obtained by using the old prescriptions from Matteucci et al. (1995) and Paper I, respectively. In particular, in Paper I we used a conservative estimate of the PN mass ejected by AGB stars:

$$M_{PN} = 0.8 \times M_{init} - 1.1$$

as in Matteucci et al. (1995). This formula accounts for any mass loss by winds prior to the ejection of the PN. The abundance of ^{7}Li in the ejected material was assumed to be $\log \epsilon(^7\mathrm{Li}) = 3.5$ dex, fairly lower than the value suggested by Matteucci et al. (1995) (4.15 dex). In both models ^{7}Li production in AGB stars takes place only at metallicities $Z > 10^{-3}$. When the thermally pulsing AGB phase is followed by means of self-consistent stellar evolutionary tracks and mass loss is taken into account in a detailed way, more reliable ^{7}Li yields can be obtained. Chemical evolution results produced by using the model grid of Table 1 for a value of the Reimer's parameter of mass loss $\eta_R = 0.10$ are very similar to those obtained with our old prescriptions (*cf.* models labelled *Paper I* and $\eta_R = 0.10$). On the other hand, the choice $\eta_R = 0.01$ results in a significantly lower ^{7}Li production from AGBs. A value of $\eta_R = 0.01$ seems to be the preferred one in order to explain

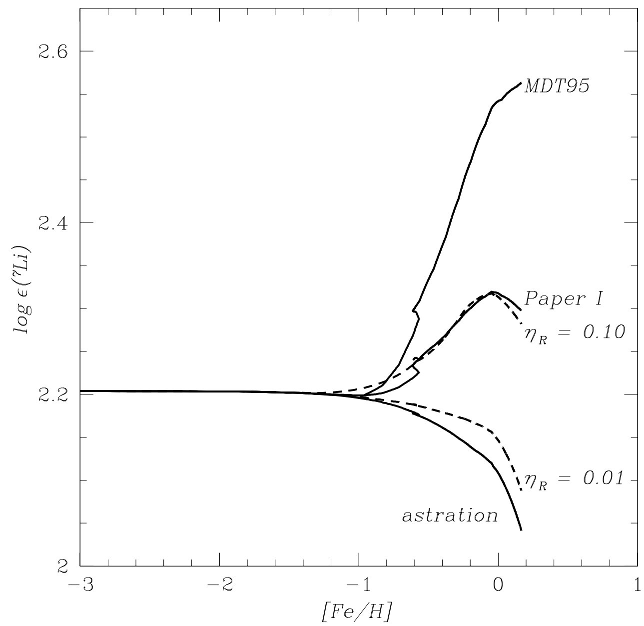

Fig. 3. *Models labelled MDT95 and Paper I*: the prescriptions of Matteucci et al. (1995) on ^{7}Li production from AGB stars are adopted – ^{7}Li production is allowed only at metallicities $Z > 10^{-3}$; the mean ^{7}Li abundance in the ejecta is $\log \epsilon(^7\mathrm{Li}) = 4.15$ (*MDT95*) or 3.5 (*Paper I*). *Dashed lines* are models which include the grid of stellar yields given in Table 1, for values of the Reimer's factor η_R equal to 0.1 or 0.01, respectively. As the lower value of η_R is the preferred one, we can conclude that the contribution from AGB stars to the overall Galactic ^{7}Li enrichment is negligible (compare results on AGB stars to the case of pure astration shown on the bottom of the figure).

some important stellar observational properties (Ventura et al. 2000); hence we conclude that ^{7}Li production from AGB stars should be negligible and nearly undistinguishable from a situation where only astration is acting and no astrophysical sites for lithium production are turned on (model labelled *astration* in Fig. 3).

In Fig. 4 we show the ^{7}Li abundance evolution that would be predicted by taking into account only a single category of stellar ^{7}Li producers (Type II SNe, AGB stars, novae, and low-mass giants), and compare it to the observational data. Lithium synthesis prescriptions for each class of sources are those given in Section 2.2. The sudden increase in $\log \epsilon(^7\mathrm{Li})$ at [Fe/H] ~ -0.5 pointed out by the data requires important production at Galactic ages larger than ~ 2.5 Gyr, so that a low-mass stellar component must enter in the model. It is immediately seen how novae and low-mass giants, contributing to ^{7}Li enrichment on longer timescales than the other sources, are the best candidates for explaining this late, sudden rise from the lithium-metallicity plateau. As far as the low-mass giants are concerned, the delayed lithium production is essentially due to the long lifetimes of their progenitors

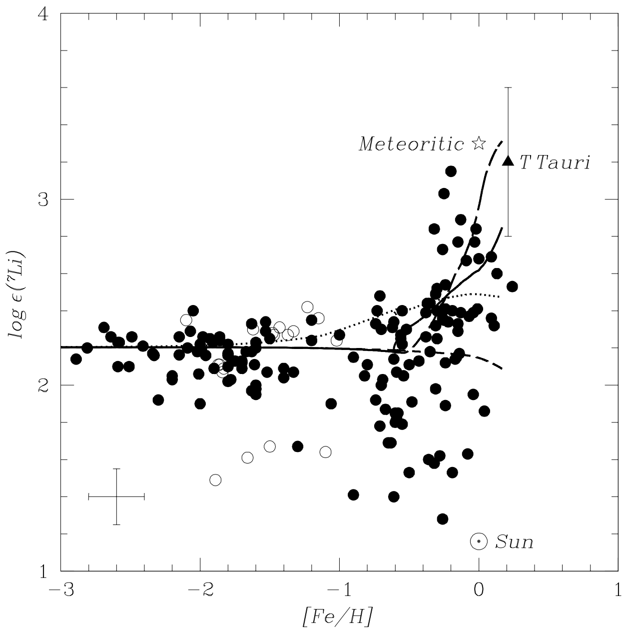

Fig. 4. $\log\epsilon(^7\mathrm{Li})$ vs. [Fe/H] theoretical trends predicted by different models compared to observational data of Fig.1. Each model takes into account ^{7}Li synthesis in a single category of stellar producers: *dots*: Type II SNe; *short-dashed line*: AGB stars (case $\eta_R = 0.01$); *continuous line*: novae; *long-dashed line*: low-mass giants.

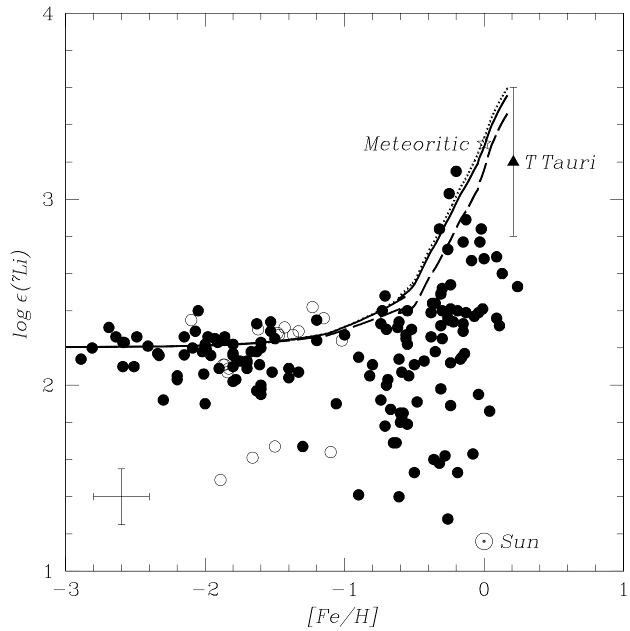

Fig. 5. $\log\epsilon(^7\mathrm{Li})$ vs. [Fe/H] theoretical trends predicted by models including all the following astrophysical sites for ^{7}Li production: *dashed line*: Type II SNe + AGB stars + low-mass giants + novae; *continuous line*: Type II SNe + AGB stars + low-mass giants + novae + GCRs. This latter is our best-model. Adding the contribution from LMXBs as discussed in the text does not change much the result (*dotted line*).

whereas, when considering novae, the late lithium enrichment is partly due to the addition of a suitable cooling time to the lifetime of the WD progenitor, which allows the newly formed WD to cool at a level that ensures strong enough nova outbursts. We checked the model behaviour under different assumptions on the value of the cooling time, and found that no relevant changes in the results are produced for values lying in the range $\Delta t \sim 1-2$ Gyr. Similarly, changing the fraction of the WDs that enter the formation of new nova systems at every time (anyway keeping it always constant over the time), so that the range of values of the present time nova outburst rate as inferred from observations can be reproduced, does not seriously affect the results. In conclusion, as far as the nova contribution is concerned, the major uncertainties reside in the nucleosynthesis computations and in the number of outbursts experienced by the typical nova system.

Given the low percentage of low-mass Li-rich stars observed in the Galaxy, we did not considered low-mass giants as ^{7}Li producers in Paper I. However, both observational and theoretical evidence has grown suggesting that this particular category of stars could eventually represent a non-negligible ^{7}Li factory on a Galactic scale (see Section 2.2.3). Therefore, we include now in the code ^{7}Li production from low-mass giants as well. We find that a significant contribution from these stellar sources is achieved only under very restrictive hypotheses on the parameters of the lithium enhancement: lithium enhancement has to last for a period of $\sim 10^7$ yr; moreover, the enhancement has to occur in conjunction with strong mass loss rates. This latter requirement can be easily satisfied if lithium enrichment occurs near the tip of the RGB.

Table 2. Percentage of meteoritic ^{7}Li contributed from each source in the framework of our best-model.

Source	%
Type II SNe	9%
AGB stars	0.5%
low-mass giants[a]	41%
novae	18%
GCRs	25%

[a] $1 \leq M/M_\odot \leq 2$.

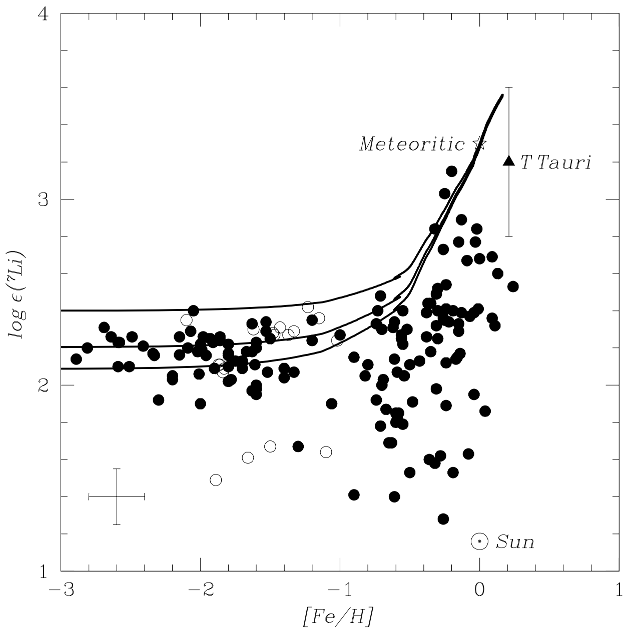

Fig. 6. Model predictions are compared to observational data. We show the effect of changing the primordial lithium abundance (from bottom to top: $\log \epsilon(^7\mathrm{Li})_P$ = 2.09, 2.2, and 2.4 dex).

3.2. Our best-model

By taking into account all the stellar ^{7}Li producers seen above in the chemical evolution model, we are able to explain the steep rise from the lithium-metallicity plateau, but we still fail to achieve the meteoritic abundance of ^{7}Li (Fig. 5, dashed line). Our best-model includes the contributions from Type II SNe, AGB stars, low-mass giants, novae and GCRs (Fig. 5, continuous line). Adding the contribution from LMXBs practically does not change the result (Fig. 5, dotted line). This is against LMXBs being considered lithium producers on a Galactic scale, although no firm conclusions can be drawn, given the uncertainties involved when dealing with these systems. However, we would like to stress that we adopted here a series of prescriptions aiming at maximizing the role of LMXBs in enriching the ISM with Li, at least in the framework of our present knowledge of these systems (see Section 2.2.6). In Table 2 we list the contribution (in %) to the meteoritic abundance from each source in the framework of our best-model. The joint contributions from Type II SNe, AGBs, and GCRs are able to explain $\sim 35\,\%$ of the meteoritic ^{7}Li abundance. The remainder should be produced by long living sources, which we identify with novae and low-mass giants. However, the relative importance of their contributions is very uncertain. We tentatively ascribe $\sim 20\,\%$ of the meteoritic lithium to nova production and $\sim 40\,\%$ to low-mass giants, on the ground of current knowledge of nova nucleosynthesis and current (un)knowledge of ^{7}Li synthesis along the RGB in low-mass stars.

Finally, we compare our best-model with other two models which share with it the same prescriptions on ^{7}Li production, but start from different values of the primordial lithium abundance (Fig. 6). It is worth noticing that model results are nearly the same for metallicities greater than [Fe/H] ~ -0.5. This is due to the fact that stellar astration acting during the Galaxy evolution strongly reduces the primordial ^{7}Li abundance in the ISM already after ~ 2.5 Gyr from the beginning of the Galaxy formation[2]. For $t > 2.5$ Gyr only a small fraction of the observed ^{7}Li has a primordial origin, since at that time most of the ISM ^{7}Li abundance is due to stellar production.

4. Conclusions

- In agreement with our previous results (Paper I) we confirm that novae are necessary in order to reproduce the ^{7}Li abundance evolution traced out by the upper envelope of the observational data; in particular, they can reproduce the steep rise of the lithium abundance for [Fe/H] ≥ -0.5 dex.
- New stellar yields of ^{7}Li from AGB stars have been included in the code for the chemical evolution of the Galaxy. As a result, we find that AGB stars cannot be considered as a significant source of ^{7}Li in the Galaxy.
- Low-mass giant stars, restoring their processed material on long timescales, are among the best candidates (together with novae) for reproducing the late rise from the lithium-metallicity plateau. Recent theoretical computations (Sackmann & Boothroyd 1999) suggest that they could indeed contribute a non-negligible fraction of the interstellar ^{7}Li, and this is confirmed by our model results. However, it should be cautioned that in order to reproduce the observed $\log \epsilon(^7\mathrm{Li})$ vs. [Fe/H] trend we have to make very restrictive hypotheses on the parameters of the lithium enhancement in low-mass RGB stars.
- As far as the LMXBs are concerned, we conclude that they contribute negligibly to the amount of lithium in the Galaxy.
- The temporal evolution of the ^{7}Li abundance in the disk is almost independent of the value of the primordial abundance we choose. On the contrary, the evolutionary scenario in the halo is deeply bound to the choice of this value.
- Our best-model predicts an increase in the ISM ^{7}Li content over the last 4.5 Gyr. At first glance, this seems to be in disagreement with recent observations both of T Tauri stars (Stout-Batalha et al. 2000) and in the Orion association (Cunha, Smith, & Lambert 1995). However, as far as the Orion stars are concerned, there

[2] In the framework of the model presented here, an ISM metallicity of [Fe/H] ~ -0.5 is gained at $t \sim 2.5$ Gyr.

are arguments for accommodating a ^{7}Li abundance near-solar even if the Galactic disk ^{7}Li abundances are increasing (Cunha et al. 1995): in particular, the fact that the mean [Li/Fe] for the Orion stars is roughly 0.0 to -0.1, and therefore not very far from the meteoritic value, would be indicative of the fact that the ^{7}Li content measured in the Orion association should not be compared to our results for the ^{7}Li abundance in the ISM at the present time, but with those referring to 4.5 Gyr ago.

Finally, we would like to recall the reader that all our computations have been carried out under the assumption that the stars tracing the upper envelope of the $\log \epsilon(^7\text{Li})$ vs. [Fe/H] diagram have not had their original lithium abundance altered by any process of dilution and/or depletion.

Acknowledgements. We acknowledge an anonymous referee for the helpful criticism.

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